CHEMICAL ENGINEERING TRANSACTIONS Volume 19, 2010
Editor Simberto Senni Buratti
Copyright © 2010, AIDIC Servizi S.r.l., ISBN 978-88-95608-11-2 ISSN 1974-9791
DOI: 10.3303/CET1019044

Life Cycle Assessment of Soybean Biodiesel and LPG as Automotive Fuels in Portugal

Sérgio Morais[1], Teresa M. Mata[2], Eugénio Ferreira[3]

[1]REQUIMTE - Rede de Química e Tecnologia / School of Engineering (ISEP), Polytechnic Institute of Porto, R. Dr. António Bernardino de Almeida, 4200-072 Porto, Portugal

[2]LEPAE - Laboratory for Process, Environmental and Energy Engineering / Faculty of Engineering (FEUP), University of Porto, R. Dr. Roberto Frias S/N, 4200-465 Porto, Portugal

[3]CBE - Centre of Biological Engineering / School of Engineering (EENG), University of Minho, Campus de Gualtar, 4710-057 Braga, Portugal

This study aims to compare soy methyl esters (biodiesel) and liquefied petroleum gas (LPG) as automotive fuels in Portugal using LCA. The potential environmental impacts (PEI) associated with their life cycles are compared for twelve impact categories. As a general conclusion biodiesel has a lower total PEI than LPG. Nonetheless biodiesel shows higher values of some individual impact categories such as acidification, photo-oxidant formation, terrestrial eutrophication, and land use. This study results can be used to support decision making and recommendations about the environmentally preferable fuel to be used in Portugal, which should be complemented with economic and societal considerations.

1. Introduction

The increasing awareness about global warming and fossil fuels depletion led to several environmental studies about energy and greenhouse gas balances of both conventional and alternative automotive fuels over their whole life cycles (e.g. Beer *et al.*, 2002; Concawe-Eurocar, 2006; Zah *et al.*, 2007). LPG and pure biodiesel (called B100) are two alternatives to the conventional automotive fossil fuels (petroleum diesel and gasoline) with a widespread commercial use in Portugal. In 2008 LPG sales totalled 24418 metric tons and B100 totalled 4800 metric tons (DGEG, 2008). The consumption of Compressed Natural Gas (CNG) as automotive fuel is still residual due to infrastructure and market barriers (Concawe-Eurocar, 2006). Concerning LPG and Biodiesel, there is still a lack of a comprehensive environmental comparison between both fuels, especially for a Portuguese context. Also, existing studies normally do not cover important PEI categories, such as land use impacts and eco-toxicity in different environmental compartments (e.g. soil, oceanic and surface waters). Moreover, LCA results are highly dependent on the geographical coverage in which the study is based and cannot be directly used in other regions of the world.

Please cite this article as: Morais S., Mata T. and Ferreira J.F., (2010), Life cycle assessment of soybean biodiesel and lpg as automotive fuels in portugal, Chemical Engineering Transactions, 19, 267-272 DOI: 10.3303/CET1019044

2. Case study: Biodiesel versus LPG

2.1 Goal and scope definition

The goal of this LCA study is to compare LPG and soybean biodiesel used as automotive fuels in Portugal. The PEI associated with both fuels life cycle are evaluated, highlighting the most critical environmental aspects and then, they are prioritized in terms of their environmental performance.

The principles and framework for conducting and reporting LCA studies, described in the international standard EN ISO 14040 (2006) and Guinée (2002), have been followed in this study.

The functional unit chosen in this study as a reference in relation to which the inventory data was gathered is 1MJ of useable energy from a vehicle engine driveshaft. It is considered for LPG and soybean biodiesel fuel efficiencies in heavy-duty vehicles of 41.23MJ/kg and 40.67MJ/kg, respectively (NBB, 1995).

Figure 1 represents a schematic diagram of both fuels' life cycles, showing the material and energy flows or inputs and outputs within the system boundary. For simplifying the comparison a streamlined LCA approach is adopted, which excludes from the system boundary the identical life cycle stages of both fuels. Therefore, processes related to road infrastructure, vehicle manufacture and maintenance, and vehicle end-of-life management are not considered in the inventory analysis.

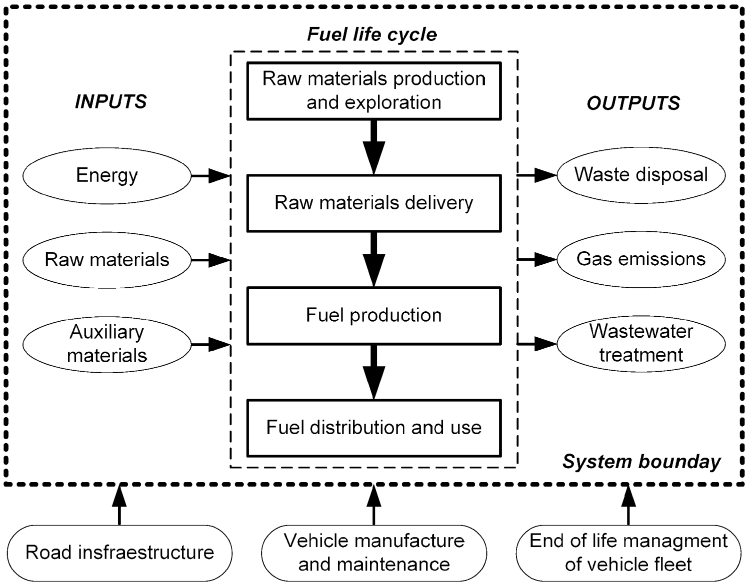

Figure 1- System boundary definition for LPG and soybean biodiesel life cycles

2.2 Inventory data and underlying assumptions

When dealing with multi-output processes as it is the case of this LCA study an allocation approach should be used to model the inventory analysis. Allocation can be defined as the partitioning or assignment of material inputs and environmental releases or outputs among the main products or co-products and wastes in a multi-output process. The environmental burdens are assigned to them according to 'weighting factors' or 'allocation factors', representing the proportion of an output relatively to the other, which can be based on mass flow, energy value, or economic revenue of co-products. In this study an economic allocation approach was used, as proposed by Guinée (2002), where the environmental burdens are distributed among co-products proportionally to their revenue and based on three consecutive annual average prices from 2006 to 2008.

An inventory analysis was performed for LPG and soybean biodiesel life cycles for which data was gathered from literature, available databases, and typical Portuguese/European production units. For example, the inventory data for typical steam and electricity production units in Western Europe or Portugal was obtained from Frischknecht (1996) and BUWAL 250 (1996).

Soybean biodiesel can be produced in Portugal, but soybean oil is imported from U.S. or Brazil where soybeans are grown and their oil is extracted. This is because in Portugal the climate and type of soil are not suitable to growth that type of crop. Biodiesel is produced in a conventional alkalis catalysed transesterification process that is of widespread industrial use today. For this process average data is given by Sheehan *et al.* (1998) as well as for other associated processes, such as methanol and sodium methoxide production, used as reagent and catalyst respectively.

For LPG, the inventory analysis considers the crude oil extraction and the LPG production and use in vehicles, for which average data are available in BUWAL 250 (1996), Frischknecht (1996) and Beer *et al.* (2002). Beer *et al.* (2002) also presents average data of tailpipe combustion emissions of LPG and soybean biodiesel in heavy-duty vehicles. Portugal imports crude oil from several countries such as Nigeria, Venezuela, Angola, Algeria and Middle East. For crude oil transportation, average distances were calculated considering the overseas distances between those countries and Portugal. Each distance was corrected by a factor representing the fraction of crude oil transported in each route in a yearly basis, relatively to the total crude oil imported.

2.3 Life Cycle Impact Assessment

For the PEI assessment characterization models were used (Table 1), as proposed by Pennington *et al.* (2004) on a comprehensive and extensive review.

Table 1. PEI categories and respective characterization models

Impact Category	**Unit**	**Characterization Model**
Global warming	kg CO^2 eq	IPCC´s GWP
Stratospheric ozone depletion	kg CFC-11 eq	WMO´s ODP
Human toxicological effects (carcinogenic and non-carcinogenic)	DALY [(a)]	USES-LCA 2.0
Photo-oxidant formation	YOLL [(b)]	EcoSense
Freshwater aquatic ecotoxicity	1,4-DCB eq	USES-LCA
Marine aquatic ecotoxicity	1,4-DCB eq	USES-LCA
Terrestrial ecotoxicity	1,4-DCB eq	USES-LCA
Acidification	1,4-DCB eq	EPS version 2000
Aquatic eutrophication	kg PO42- eq	EPS version 2000
Terrestrial eutrophication	kg wood	RAINS-LCA
Land use impacts	PDF×m^2×year/m^2	Eco-Indicator 99
Abiotic resources depletion (fossil and non-fossil)	kg antimony eq	Eco-Indicator 99

(a) DALY: Disable Adjust Life Years.

(b) YOLL : Years of Life Lost.

Normalized PEI categories (Nk) were calculated (according to Eq.1) by dividing each PEI category (Sk) by its reference PEI value (Rk) obtained, for example, from a particular reference year or geographical location (Pennington *et al.*, 2004).

$$N_k = \frac{S_k}{R_k} \tag{1}$$

The reference PEI values (Rk) applied in this study were calculated using as reference the year of 1995 (except year 1996 for terrestrial euthrophication) and the geographical locations of Western Europe (WE) and EU-15. The normalized PEI categories were then all summed or aggregated in just one indicator or total PEI. These values are shown in Table 2.

Table 2. PEI categories (Sk), Reference PEI values (Rk), and Normalized PEI categories (Nk) for Biodiesel and LPG

Impact category	**Sk Biodiesel** (units in Table 1)	**Sk LPG** (units in Table 1)	**Rk** (units in Table 1)	**Nk Biodiesel** (dimensionless)	**Nk LPG** (dimensionless)
Global warming	2.4339×10^{-01}	1.3127×10^{-01}	$4.8125\times10^{+12}$	5.0574×10^{-14}	9.2324×10^{-14}
Stratospheric ozone depletion	4.3613×10^{-08}	4.8725×10^{-07}	$8.3000\times10^{+07}$	5.2546×10^{-16}	1.8724×10^{-14}
Human Toxicological Effects	9.2931×10^{-08}	2.9537×10^{-07}	$3.2092\times10^{+06}$	2.8958×10^{-14}	2.9411×10^{-13}
Photo-oxidant formation	3.2456×10^{-06}	6.1199×10^{-07}	$1.4164\times10^{+10}$	2.2915×10^{-16}	1.3821×10^{-16}
Freshwater aquatic ecotoxicity	1.5793×10^{-03}	4.8073×10^{-03}	$5.0500\times10^{+11}$	3.1273×10^{-15}	3.0385×10^{-14}
Marine aquatic ecotoxicity	$1.2952\times10^{+01}$	$2.8878\times10^{+01}$	$1.1000\times10^{+14}$	1.1775×10^{-13}	8.3864×10^{-13}
Terrestrial ecotoxicity	5.2734×10^{-04}	7.4082×10^{-04}	$4.7000\times10^{+14}$	1.1220×10^{-18}	5.0302×10^{-18}
Acidification	5.6140×10^{-03}	9.1158×10^{-04}	$3.5005\times10^{+10}$	1.6038×10^{-13}	8.4241×10^{-14}
Aquatic eutrophication	6.4384×10^{-07}	2.1744×10^{-18}	1.4642×10^{-02}	5.3653×10^{-17}	4.7367×10^{-16}
Terrestrial eutrophication	6.8011×10^{-03}	8.5887×10^{-04}	$6.0837\times10^{+10}$	1.1179×10^{-13}	4.6626×10^{-14}
Land use impacts	1.8611×10^{-01}	8.8670×10^{-03}	$1.5000\times10^{+12}$	1.2408×10^{-13}	1.8909×10^{-14}
Abiotic Resources Depletion	6.2983×10^{-04}	9.3036×10^{-04}	$1.5000\times10^{+10}$	4.1989×10^{-14}	1.9784×10^{-13}
Total PEI				$\mathbf{6.3945\times10^{-13}}$	$\mathbf{1.6224\times10^{-12}}$

2.4 Results and Discussion

LPG shows higher environmental impacts than biodiesel for almost all the PEI categories except for acidification, photo-oxidant formation, terrestrial eutrophication and land use. As shown in Table 2 the total PEI of LPG is 2.54 times higher than that of soybean biodiesel.

Figure 2 shows the LPG contribution to the normalized PEI in each life cycle stage.

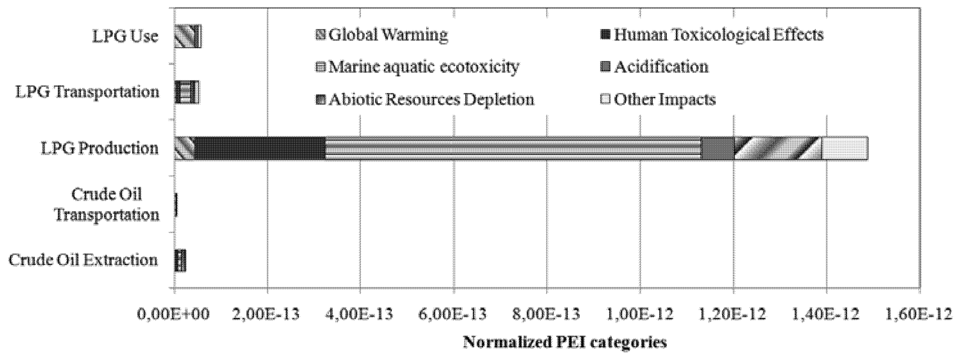

Figure 2 - Contribution of LPG to the normalized PEI in each life cycle stage

LPG production is by far the most significant life cycle stage in terms of PEI representing 92.29% of the normalized total PEI (Figure 2). Marine aquatic ecotoxicity is the major impact category contributing to 51.69% of the total PEI where 50.88% is due to LPG production.
In refining processes, the emissions of heavy metals are relevant pollutant contributors to the aquatic environment. In this study, emissions of barium, cobalt, nickel, selenium and vanadium emitted to air and water represent 73.60% of the marine aquatic ecotoxicity in LPG production.

Figure 3 shows the contribution of soybean biodiesel to the normalized PEI in each life cycle stage.

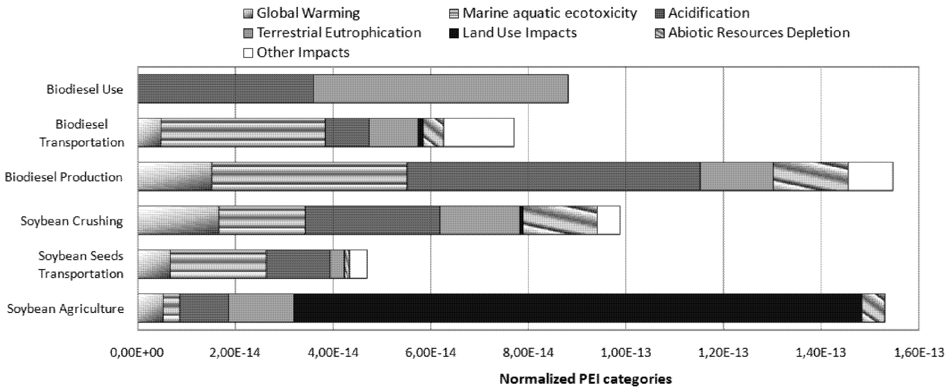

Figure 3 - Contribution of biodiesel to the PEI in each life cycle stage

Agriculture and biodiesel production are the two most significant life cycle stages in soybean biodiesel life cycle, representing almost half of the total normalized PEI (Figure 3) and acidification is the most significant impact category (Table 2). Biodiesel production has a relevant contribution to acidification mainly due to nitrogen and sulphur oxides emissions during steam production both representing 80.16 % of the total acidifying emissions. Land use impacts (due to occupation and transformation) account for 76.02% of PEI in the soybean agriculture stage.

3. Conclusions

This study performs an LCA study to compare two alternative fuels used in Portugal: LPG and soybean biodiesel. As main result soybean biodiesel is the environmentally preferable fuel since it has a total PEI 61% lower than LPG. The main driver for the adoption of biodiesel relatively to conventional fuels is the need to reduce greenhouse gas emissions and depletion of abiotic resources. This study shows that soybean biodiesel contributes to 45% and 79% lower global warming and abiotic resources depletion respectively, in comparison to LPG. In particular, marine aquatic ecotoxicity and human toxicity are much lower for biodiesel in comparison to LPG. However biodiesel shows a higher contribution to some individual impact categories such as acidification, terrestrial eutrophication and land use that are respectively, 47%, 58% and

85% higher than for LPG. Other important PEI categories associated with biodiesel are the deforestation of tropical forests and biodiversity loss due to feedstocks production and increase of global demand, which are not quantified in this study due to the lack of data.

References

Beer T., Grant T., Morgan G., Lapszewicz J., Anyon P., Edwards J., Nelson P., Watson H., Williams D., 2002, Comparison of Transport Fuels, Stage 2 study of Life-cycle Emissions Analysis of Alternative Fuels for Heavy Vehicles, CSIRO Atmospheric Research and Australian Greenhouse Office.

BUWAL 250, 1996, Ökoinventare für Verpackungen, Schriftenreihe Umwelt 250, Bern.

Concawe-Eurocar, 2006, Well to wheel analysis of future automotive fuels and powertrains in the European context. Well-to-Wheels Report, Version 2b.

DGEG, 2008, Vendas Mensais de Combustíveis em 2008, Direcção de Geral de Energia e Geologia. Available at: http://www.dgge.pt/. Accessed 23 March 2009.

Frischknecht R., 1996, Öko-inventare von Energiesystemen, 3th ed., ENET.

Guinée J., 2002, Handbook on life cycle assessment. Operational guide to the ISO standard, Kluwer Academic Publishing, Dordrecht, Netherlands.

EN ISO 14040, 2006, Environmental management - life cycle assessment - principles and framework, International Standard Organization, Geneva, Switzerland.

NBB, 1995, Potential Biodiesel Use in the Nations's School Bus Fleet, Sparks Companies, Inc & National Biodiesel Board in cooperation with the United Soybean Board Report, National Biodiesel Board.

Pennington D.W., Potting J., Finnveden G., Lindeijer E., Jolliet O., Rebitzer G., 2004, Life cycle assessment Part 2: Current impact assessment practice, Environment International, 30: 721-739.

Sheehan J., Duffield J., Graboski M., Shapouri H., 1998, Life Cycle Inventory of Biodiesel and Petroleum Diesel for Use in an Urban Bus, NREL.

Zah R., Böni H., Gauch M., Hischier R., Lehmann M., Wäger P., 2007, Life Cycle Assessment of Energy Products: Environmental Assessment of Biofuels, EMPA, Bern.